DTU Library

Structural health monitoring tools for late and end of life management of offshore wind turbines

McGugan, Malcolm; McKirdy, Scott

Published in:
Proceedings of the 8th European Workshop on Structural Health Monitoring, EWSHM 2016

Publication date:
2016

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
McGugan, M., & McKirdy, S. (2016). Structural health monitoring tools for late and end of life management of offshore wind turbines. In *Proceedings of the 8th European Workshop on Structural Health Monitoring, EWSHM 2016* (Vol. 4, pp. 2420-2429). NDT.net.

Structural Health Monitoring tools for late & end of life management of Offshore Wind Turbines

Malcolm MCGUGAN[1] and Scott MCKIRDY[2]

[1] DTU Wind Energy, Frederiksborgvej 399, dk-4000, Roskilde, DENMARK mamc@dtu.dk
[2] IDCORE, University of Strathclyde, UK S.Mckirdy@ed.ac.uk

Key words: Offshore Wind, Operation Maintenance Repair, Condition Monitoring, End of life.

Abstract

The late and end of life stages in an offshore wind turbines (OWT) life cycle have unique features that must be considered. The initial focus on risks associated with start-up issues due to design, manufacturing or process elements gives way to a stable period of operation and maintenance optimisation and service condition monitoring. However, as with other *structures, in time the issues of "wear and tear" and remaining life assessment become* increasingly prevalent. The dynamics of operating an offshore wind farm varies considerably from existing oil & gas structures. With lower operating margins and the predominance of low redundancy structures, accurate structural health monitoring can play a strong role in safe management and enable increased operating time at end of life and decommissioning. Late life operations of offshore wind farms can pose significant challenges, balancing the potential for rising operations and maintenance costs with the ability to generate significant profitability from increased reliability and longer operations. Improvements in SHM can lead to corresponding improvements in the availability and management of offshore structures. The ability to accurately gather data on damage states and thus remaining life results in significant reduction in repair costs and the determination of cost effective decommissioning plans. Under given scenarios for end of life management and decommissioning there will be various structural systems that will provide hard limits on the viable economic lifetime of OWT and their associated farms. Using a risk based review of age and decommissioning related issues a breakdown of common damage and its causes can be presented, and from this both available and developing SHM techniques to address these late life issues are identified.

1 INTRODUCTION

In the last ten years over 10GW of offshore wind power capacity has been installed in and around the North Sea. The Global installed capacity was reported as 12GW by the Global Wind Energy Council (www.gwec.net) in 2015 and there is an industry target of 150GW installed global capacity by 2030. This rapid expansion in offshore capacity from 2010 to 2030 is set to mimic the rapid expansion of onshore wind power that took place between 1995 and 2015; see figure 1.

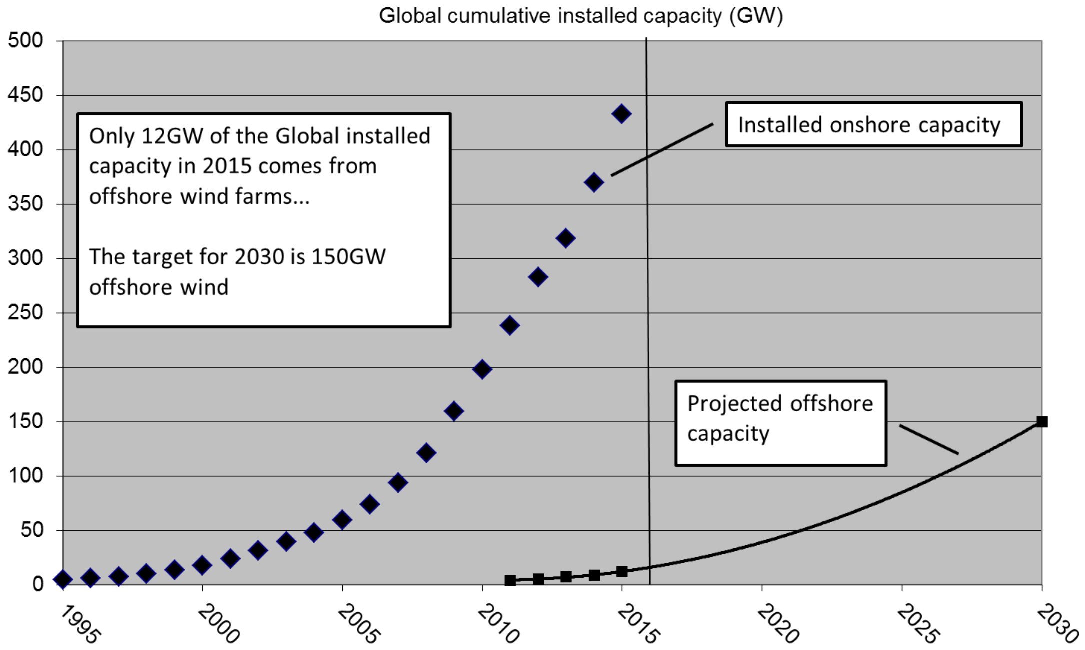

Figure 1: Global Wind Power installed capacity (from statistics available on www.gwec.net)

Many new offshore wind farms are being commissioned, not only in Europe but around the world. This also mimics the history of onshore wind power technology which was developed and demonstrated in Europe before becoming commercially installed globally. The expected lifetime of these offshore installations is at least twenty years, and after this time even components that are still in good operating condition will likely be obsolete and ready to be replaced.

The North Sea has a mature offshore oil and gas sector infrastructure that is scheduled for decommission from 2016 to 2031. In total this decommissioning activity is estimated to cost as much as $76bn [1]. This enormous sum is partly a consequence of poor planning that did not foresee and include a decommissioning process for the structures at the time they were built and installed. It is vital that the wind industry learns from the earlier planning failures of energy installations offshore and conducts due diligence for decommissioning of all wind farms and updates this documentation with the best available information.

Structural Health Monitoring tools implemented specifically to address late and end of life management decisions will have a key role to play in this process.

2 OPERATION, MAINTENANCE AND REPAIR

2.1 Component failure rates and cost effective maintenance strategy

Table 1 shows an overview of the failures reported on commercial wind turbines collected from two sources. The first source [2] is from 2007 and compiles data from 1,500 wind turbines and up to 15 years of operating information. The second source [3] is from the 2016 maintenance report compiled by the Wind Energy Update group covering twenty years of reliability information comprising 5.9GW of wind turbines, operation and maintenance industry surveys, and interviews with industry executives.

The figures from 2007 and 2016 are broadly comparable in showing mechanical and structural failures accounting for around 50% of all wind turbine failure and repair effort in both cases; the remainder are generally classified as electrical issues. The highlighted components are those where an increase in the failure % has been observed.

Mechanical / Structural component failure %			**Electric / Control component failure %**		
	Hahn (2007)	**WEU OMR (2016)**		**Hahn (2007)**	**WEU OMR (2016)**
Drive Train	2	2	Electrical system	23	22
Gearbox	4	5	Plant control system	18	16
Generator	4	6	Sensors	10	10
Structural housing	4	7			
Rotor hub	5	4			
Mechanical brakes	6	5			
Rotor blades	7	8			
Yaw system	8	7			
Hydraulic system	9	8			
Total	**49**	**52**		**51**	**48**

Table 1: Overview of reported failures (as %) on commercial wind turbines

The 2016 maintenance report [3] makes the following general conclusions from the information collected:-

- Electrical components are the leading single cause of lost days however they are fixed quickly and usually cause less than one day of power outage.
- Gearboxes account for only 5% of the reported failures but cause the longest power outages; an average of 5.4 days.
- The correct Operation and Maintenance strategy depends on the size of the wind farm. Installing sensors and software to allow a predictive strategy leads to earlier detection of failures and better overall performance – however it is not always cost effective due to higher investment costs. For wind power plants up to 200MW, a scheduled maintenance strategy is the most cost effective.

Operation, maintenance and repair strategies can be broadly classified as follows:-

i. Reactive – fix something once it has failed
ii. Preventative – regular fixed-schedule maintenance
iii. Predictive / condition-based – monitoring the rate of deterioration/performance
iv. Reliability centred – data from past records are used to schedule parts replacement

The WEU O&M survey [3] reports that 25% of operators surveyed have a reactive strategy while 50% adopt a preventative strategy. It follows that predictive and reliability centred strategies account for the remaining 25%. However there is one truly critical issue missing from this publically available data; these figures are for onshore wind power only. True figures for offshore operation are more difficult to obtain, but the accessibility issues for offshore wind farms (which also tend to be far larger in terms of power production than those onshore) make potential savings from successfully applied predictive and reliability O&M strategies more likely.

For example, electrical systems fail frequently but are easy to fix and this promotes a programmed (scheduled) maintenance approach. Generators, gearboxes and drive train failures have the most effect on power production, but are not reported nearly so frequently as the electrical systems and this promotes a reactive (unscheduled) maintenance approach; at least for onshore wind farms.

The hydraulic system, yaw system, rotor hub issues, mechanical brake failures and the rotor blades are somewhat in between these two situations being components that have semi-frequent failure rates and a relatively significant effect on power production from undetected failure. These components are the ones where a move to a more preventative maintenance strategy is likely to be the most beneficial.

2.2 Blade failure

15-20% of the total cost of ownership for a wind turbine can be associated with the rotor blades [4]. Blade failures in operating wind turbines are often publically identified as being due to <u>manufacturing</u> defects or <u>design</u> issues. For example:-

i) Wrinkles in the reinforcing laminate (formed during manual lay-up process) act as stress concentration for initiation of delamination damage – Manufacture issue!
ii) Cracking at shear web attachment leading to debonding – Design issue!
iii) Leading edge protection failure – Design/Manufacture issue!
iv) Root section adhesion failure – Manufacture issue!
v) Sandwich interface debonding at curvature – Design issue!

The other large group of blade failures are attributed to <u>lightning</u> strikes and the build-up of <u>ice</u>. Manufacturing and design are classic burn-in period type failures as illustrated in the "bathtub" curve for component failure.

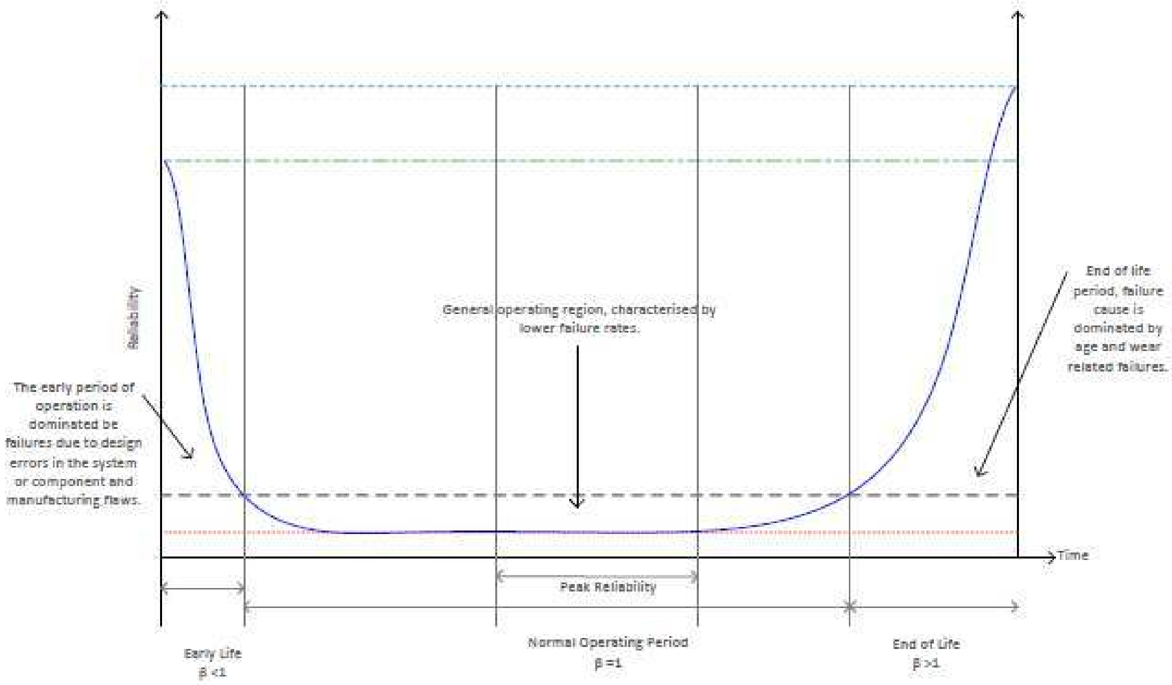

Figure 2: "Bathtub" curve for component failure

On the other hand lightning damage is primarily a seasonal risk based on the geographical placement of the wind turbine and the tip height; similarly ice accumulation is also a seasonal site-specific risk. Risk of operational issues due to lightning and ice are present throughout the wind farm life cycle.

Wind turbines are designed to be in continuous operation for at least twenty years. The big issue of aging effects due to many years of service loadings (wear) or environmental effects (on the blade matrix material and at interfaces) are largely missing from these reviews, but are sure to be among the wear-out period issues at the other end of the bathtub (see figure 2) that a decommission process must address.

In order to gain reliable information about the extent to which operational loading and environment has reduced remaining lifetime for the blades in a wind farm, a combination of destructive and non-destructive material testing could be commissioned in a mid-life structural assessment. Alternatively a "fleet leader" could be identified and inspection and the monitoring regime implemented here used to give and early warning of burn-out issues that can be checked for and mitigated against throughout the rest of the fleet. The issue with both these approaches is to ensure that local effects and structure specific effects are accounted for without full fleet global structure inspection and monitoring.

On-site repair of damage blades is not a simple task. For this reason detecting defects in these components at an early stage is important to minimise the requirement for complex procedures onsite, or worse, blade removal. Visual inspection (both inside and outside the blade) by an experienced technical expert is the most effective tool in uncovering local whitening/cracking, adhesive failures, discontinuities, delamination within the laminate, de-bonding, and surface erosion. This "close to the hands" inspection by an expert can be supported by high resolution photography from the surface (or by drone inspection) but in almost all cases a local inspection will also be required to make a confident defect assessment.

In some cases non-destructive inspection tools such as ultrasound, x-ray inspection or vibrometry can be used to uncover invisible (barely visible) damage or to more fully characterise a defect that has been observed visually.

2.3 Monitoring and inspection tools

As well as these inspection tools, there is also data generated by monitoring sensors. When undergoing certification testing, blades can be instrumented with conventional strain sensors (point measurements), accelerometers (global vibration measurements), possibly acoustic emission sensors (local stress-wave activity) and other technologies in order to check the response to both static and dynamic loading against models, and to highlight any deviations in expected response that could be due to the generation of damage. These have also been the most common techniques applied for operational measurements on prototype and demonstration turbines, although fibre optic based strain measurement systems are also common now. It should be noted that commercially produced blades are generally not instrumented with any form of damage detection sensors, although in some cases these can be retro-fitted on-site.

Companies such as Gram and Juhl (http://gramjuhl.com/) can provide turbine condition monitoring systems based on vibration sensors that specifically provide early failure detection for the cost-intensive components within the nacelle; gearbox, main bearing, and other drive train components. These measurements will also uncover rotor imbalance that could be due to changes in the blade stiffness as a result of extensive damage within blades.

However this effect will generally be detected only at a stage when minor, preventative, on-site blade repair is no longer an option.

Therefore, in order to focus the manual blade inspection and repair effort, conducted every season for offshore installations, many operators would like to develop early warning systems similar to that available for the gearbox, specifically for the blades. The most promising technologies rely on carefully positioned accelerometers measuring the (edgewise) vibration frequencies and changes to these that are a result of damage causing a local drop in structural stiffness.

Commercial systems to measure the fluctuating root strain in operating turbine blades are already available (http://www.fibersensing.com/market/wind). This data can be applied and integrated within the turbine control system in many ways; for Pitch control, Condition monitoring, Load assessment, Design validation, Vibration monitoring and Ice detection.

To fully develop this area however it would be necessary to initiate a comprehensive blade monitoring program approach that can;

- Identify all critical failures
- Perform sensitivity studies with the most promising technologies
- Initiate technology testing on prototype blades (demo platforms)

3 CONDITION MONITORING TECHNOLOGY MATCHED TO DAMAGE

It is likely that towards the end of life, the question of how to address an issue that becomes an “uptick” in reported failures at the “burn-out” end of the bathtub diagram (fig.2) for a specific component will only be raised when that issue is already becoming prevalent. At that point an effort will be made to detect, understand, and solve the issue; once implemented this solution will allow the structure to continue as before until, inevitably, another “uptick” issue becomes known. At some point the issue encountered will not be simple to solve, or a combination of different issues arising simultaneously will suggest that the best option is to go to a decommission process.

The blade inspection tool kit and any installed monitoring technology can be used to help make more effective Operation, Maintenance and Repair actions; this has been surveyed by various authors [4],[5],[6],[7],[8],[9]. However the data so gathered can also be used to generate information that will be valuable when making decisions about the correct mitigation action for a “burn out” issue for a specific component, and ultimately the optimal end of life strategy to pursue for the entire wind farm.

In table 2 a set of example issues (not comprehensive) for the turbine blades have been matched against suggested monitoring and control techniques that can mitigate or at least provide valuable details about that problem. Some are established issues, while the others will be encountered either in late life operational components or the next generation / new design components. The matched monitoring/control solution has a Technological Readiness Level (TRL) that indicates how mature the technique is in relation to Industrial application. This classification can also be used to focus effort, with the topics to the left and upper part of the table requiring implementation action and the topics to the bottom and right of the table requiring more research.

	Established problem	Solution?		Future problem	Solution?
High TRL	Rotor imbalance	Nacelle mounted accelerometers		Active load control / load avoidance	Blade root strain FBGs and hub-mounted LIDAR
Mid TRL	Structural coupling effects	Combined wind-wave multi-body Fluid Structure Interaction models for improved design, control, sensing and actuation – modal analysis		Prognosis, end of life calculations	Micro to Macro composite fatigue damage mechanism – Acoustic emission?
Low TRL	Leading edge/trailing edge damage (weathering/erosion and bond-line failures)	Understanding the mechanisms then defining risks and strategies for protection and/or avoidance		Damage tolerant to damage controlling composite structural material	Carbon nanotube doped matrix for self-sensing and biomimetic crack resistance

Table 2: Matching existing and future problems to potential monitoring solutions

4 THROUGH LIFE RISK, MITIGATING THROUGH KNOWLEDGE

Consideration of the whole lifecycle of a wind farm can give a very different perception of risk. The consequence of premature and unexpected failures can have significant impacts on the whole lifecycle performance. In particular, the performance at end of life is highly dependent upon the condition of both individual turbines and farms as a whole. When considering options available at end of life, high confidence in the condition assessment of structures and components is the key to good decision making. The impact of improved knowledge can be best emphasised by considering some of the options available for end of life management of offshore wind farms. Risk is defined as the consequence or severity of an event and its likelihood to occur, however over longer time periods and without a true objective it's impossible to quantify the consequence of failing to meet those objectives. Coupled to this the ability to accurately state a probability is only possible with improved knowledge, in particular knowledge throughout the lifecycle becomes more important when considering longer time frames and gaps and failures in the dataset can make estimation of current condition and remaining life significantly more challenging.

The impact of improved information on three common end-of-life strategies is presented here. All the end-of-life scenarios require some level of knowledge and all gain significant benefits from improved knowledge. When discussing improved knowledge, it is important to make the distinction between knowledge and data. It is important to couple data with accurate assessment methodologies; the impact of increased knowledge of the system is only positive where the data collected is useful. In particular knowledge of performance over the lifecycle can be very valuable in cases where life extension or reuse

4.1 Life Extension

Assets are refurbished and/or a new O&M plan is implemented in order to extend the estimated remaining life beyond current estimates and past original design life. This requires a significant degree of intervention and planning and may not always be possible. Life extension of marine assets is relatively well understood and common in the oil and gas industry, while the cost metrics and deployments are significantly different there may be cases where life extension makes sense either on a large scale or limited to selected facilities.

Positive Impacts from Increased knowledge and reduced risk

- Improvements can be made without significant modifications to supply chain and infrastructure.
- Can be applied to limited areas, this may be beneficial as part of an overall plan to maintain output to offset costs of a phased decommissioning or renewal.
- Can increase the overall efficiency of assets over their lifecycle, where minimal intervention is required to extend life

Negative Impacts from poor knowledge and increased risk

- Accurately assessing the effects of improvements requires a significant dataset both of previous and current performance of components and environmental analysis.
- Risks of failure in life extended assets are typically always higher due to the inability to account for all factors.
- Life extension typically requires an increase in condition based maintenance and thus an increase in condition monitoring and data.
- A combination of both destructive and non-destructive testing is likely to be required, particularly if there is a poor condition dataset prior to planning extension.

4.2 Run to Fail

Assets are run to their maximum possible lifetime without major interventions or modifications. This option will be attractive where there is little appetite for significant investment or where systems have met or exceeded design lifetimes. It represents the end of life option with the least immediate resource requirements. This will often be the initial choice during early stage decommissioning planning, however without good knowledge of operating the system it is almost impossible to accurately determine if this will be the correct option.

Positive Impacts from Increased knowledge and reduced risk

- Run to fail can be an attractive option where existing datasets indicate condition is within the desired performance envelope and the existing supply chain is stable.
- Lowest capital cost option during the operating period of the wind farm.
- Less susceptible to lack of knowledge, where it is not required as input to the O&M system the only minimal monitoring for safety purposes is strictly required.

Negative Impacts from poor knowledge and increased risk

- Lack of data can make accurate remaining life estimation difficult.
- Potentially low efficiency of assets, condition of individual components of the farm can vary significantly. The economic viability can be negatively affected by premature

failures.
- Higher likelihood of increased costs of decommissioning and higher risks from operating on poor condition assets.
- At increasing age assets will exhibit failures typical of late life that will put additional stress on O&M and supply chain.
- Determination of true failure point requires a careful analysis of assets, without good condition data assessing the safe point of failure where no further upkeep is economically viable is challenging.

4.3 Replacement, Removal & Reuse

This strategy involves the removal of wind turbines at a fixed period or condition for either total site clearance and/or replacement with newer model turbines. This is the most common option that many operators will consider as the first option. The rate of improvement in technology and the industry as a whole generally make replacement with newer generation devices on a site of known resource a more palatable option. However, there are many reasons why this option may not be available either due to the high capital cost or local economic or legislative conditions that may mandate total removal and clearance of the site.

Positive Impacts from Increased knowledge and reduced risk
- Determination of a fixed lifetime within an envelope of time, condition or both requires a significant body of knowledge.
- Having a fixed period allows a greater economic certainty and long term planning.
- Removal prior to failure state allows for better likelihood of recovery of value, parts with sufficient remaining life can be utilised to increase inventory capacity or for later resale as parts or as whole devices for redeployment under more benign operating conditions
- Can be used to extend the life of a smaller number of assets.

Negative Impacts from poor knowledge and increased risk
- High confidence in remaining life is required for accurate economic planning.
- Vulnerable to poor analysis of remaining life or unexpected failures that can negatively affect established management plan.
- Differential degradation of components can pose challenges, careful assessment of the system is required to determine bottlenecks, where failures of significant components can either invalidate the economic conditions or result in failure of the structure.

5 CONCLUSIONS

Making correct end of life decisions is an area of increasing interest for offshore wind farms. With a focus on the blade structure a set of current and future issues have been matched with possible monitoring and control solutions in order to prioritise implementation and research efforts that will support good decision making. Three end-of-life strategies are presented and the benefit of good available structural condition knowledge is highlighted.

6 AKNOWLEDGEMENTS

The authors would like to acknowledge the funding support from the Danish EUDP (Energy technology development and demonstration) project ODIN-WIND, “Decommission of Offshore Wind Turbines" - Project number 210036. EUDP is part of the Danish Government Energy Agency.

7 REFERENCES

[1] Decomworld, 8th annual North Sea Decommissioning Conference, Aberdeen 2011

[2] Hahn B, Durstewitz M and Rohrig K (2007) "Reliability of Wind Turbines - Experiences of 15 years with 1,500 WTs" Institut für Solare Energieversorgungstechnik (ISET), Universität Kassel, 34119, Germany http://renknownet2.iwes.fraunhofer.de/pages/wind_energy/data/2006-02-09Reliability.pdf

[3] The Wind Energy Operations and Maintenance Report 2016, Industry report from Wind Energy update (http://analysis.windenergyupdate.com/operations-maintenance)

[4] Li D, Ho S-C M, Song G, Ren L and Li H (2015), "A review of damage detection methods for Wind Turbine Blades" Smart Mater. Struct. 24 (2015) 033011 (24pp) doi:10.1088/0964-1726/24/3/033001

[5] Ghoshal A, Sundaresan MJ, Schulz MJ, Pai PF (2000), "Structural health monitoring techniques for wind turbine blades" Journal of Wind Engineering and Industrial Aerodynamics 85 (2000) pp309-324

[6] Hameed Z, Hong YS, Cho YM, Ahn SH and Song CK (2009), "Condition monitoring and fault detection of wind turbines and related algorithms: a review" Renewable and Sustainable Energy Reviews 13 (2009) pp1-39

[7] Hameed Z, Ahn SH and Cho YM (2010), "Practical aspects of a condition monitoring system for a wind turbine with emphasis on its design, system architecture, testing and installation" Renewable Energy 35 (2010) pp879-894

[8] Liu W, Tang B and Jiang Y (2010), "Status and problems of wind turbine structural health monitoring techniques in China" Renewable Energy 35 (2010) pp1414-1418

[9] Marquez FPG, Tobias AM, Perez JMP and Papaelias M (2012), "Condition monitoring of wind turbines: Techniques and methods" Renewable Energy 46 (2012) pp169-178